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Quantifying the contribution of meteorological factors and plant traits to canopy interception under maize cropland

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ABSTRACT

A thorough understanding of crop canopy interception is crucial for understanding the relationship between water management and agriculture in water-limited regions. The factors that influence the interception process, such as meteorological conditions and plant traits, are diverse and uncertain. We divided meteorological factors and plant traits into three groups: precipitation-related meteorological factors (including precipitation event factors and raindrop factors), non-precipitation-related meteorological factors (air temperature, relative humidity, wind speed, etc.) and plant traits (leaf area index (LAI) and mean leaf inclination angle). The contributions of groups and each variable were then quantified with respect to canopy interception. This study was based on data from 80 events over four years (2017–2020). Measurements were taken under maize (*Zea mays* L.) cropland located on the southern Loess Plateau. The canopy interception (I_c) was calculated as the difference between precipitation and the sum of throughfall and stemflow and all of I_c was assumed to be lost to evaporation in the study. Results showed that the cumulative I_c of the 80 events was 395.9 mm, accounting for 39.7% of the contemporaneous total precipitation, but the mean proportion of canopy interception during each precipitation event (I_c percentage) was greater at 57.6% because of the high interception percentage during light precipitation events (0–5 mm, totaling 37 events). Pearson correlations analysis revealed a significant positive correlation between I_c and precipitation-related meteorological factors (including precipitation amount, duration, raindrop diameter (D_{50}), terminal raindrop velocity (U_V) ($p < 0.01$) and intensity, average downward force (F_0) ($p < 0.05$)), whereas there was a significant negative correlation between I_c percentage and precipitation-related meteorological factors ($p < 0.01$) because precipitation amount was more affected by precipitation-related meteorological factors. When the results of different groups were compared, precipitation event factors (amount, duration and intensity) and raindrop factors (D_{50}, U_V, F_0,) made the highest contribution to explaining I_c (56.4%) and I_c percentage (28.3%), respectively. Both the unique effect and individual importance of plant traits to I_c and I_c percentage increased when considering the precipitation events which occurred close to the LAI measurement date. It is essential that short-term assessments are used if considering LAI in relation to I_c. Precipitation amount had the largest individual importance on I_c (30.2%, $p < 0.01$), whereas D_{50} was the analogous variable for I_c percentage (9.5%, $p < 0.05$). Our results confirmed that interception by the maize canopy accounts for an important portion of the total field water input. The data and information on the interception process presented in this study, should contribute to the understanding of the overall water balance in agroecosystem environments and improve knowledge of the interplay between agroecosystems and the environment.

1. Introduction

Although there is a lot of water on the earth, only about 2.5% of it is fresh (Oki and Kanae, 2006). These fresh waters support billions of individuals. However, human water use, climate change and other activities have caused a water crisis for many ecosystems across the world

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(Abbott et al., 2019). Dryland (delimited by a precipitation-potential evapotranspiration ratio <0.65) covers about 40% of the global landmass sustaining 38% of the world's population (White and Nackoney, 2003; Huang et al., 2017; Magliano et al., 2019). Sustainable and efficient management of dryland ecosystems requires an in-depth understanding of the water cycle, and especially of precipitation partitioning processes, which govern fresh water input into dryland ecosystems (Huang et al., 2017; Yang et al., 2019; Magliano et al., 2019).

Precipitation is a major component of the hydrological cycle in dryland ecosystems (Zhang et al., 2018). As it moves towards the ground, incident gross precipitation is intercepted by the plant canopy and partitioned into three components: throughfall, stemflow and canopy interception (I_c) (Zhang et al., 2021b). Throughfall and stemflow replenish soil water and maintain the water supply essential for plant survival (Zheng et al., 2018a). Interception, however, is the portion of precipitation retained by the plant canopy and eventually returned to the atmosphere. Interception plays an important role in ecohydrological processes by increasing evaporation and reducing the amount of water available for infiltration (Brasil et al., 2018). Studies on canopy interception processes have been conducted on various plants, all of which clearly indicated that it cannot be ignored as an important component of water balance. The amount and percentage of canopy interception varies greatly (6.9–27.2%) between climatic regions (Zheng et al., 2018b; Brasil et al., 2018), as it depends on factors such as vegetation characteristics (Wang et al., 2018; Yan et al., 2021), meteorological conditions (Kozak et al., 2007) and precipitation characteristics (Zhang et al., 2016; Grunicke et al., 2020). Some studies have examined different plant growth stages to explore the effect of precipitation factors on canopy interception (Zheng et al., 2018a). However, the importance of estimating the individual predictor from all response variables has generally been neglected in previous studies. Frasson and Krajewski (2013) indicated that the interaction between raindrops and the canopy changes the microphysical characteristics of precipitation. Brasil et al. (2018) pointed out that interception should not be assessed on an annual scale only, because the differences in I_c percentage between years are small, but the I_c percentage per event fluctuates substantially. Studies of interception carried out per event can better express the correlation between canopy interception and the factors that affect it (Zhang et al., 2016).

The majority of studies have focused on interception by plantation vegetation or natural forest stands (Wang et al., 2018; Yang et al., 2019; Grunicke et al., 2020), where annual interception commonly amounts to a quarter or more of total precipitation, as determined by field measurements or modeling (Muzylo et al., 2009; Zhang et al., 2016; Grunicke et al., 2020). As Sadeghi et al. (2020) pointed out, the majority of studies in the literature address canopy interception by trees and shrubs so crop canopy interception requires further investigation (Kozak et al., 2007; Nazari et al., 2019). Some studies have quantified various redistribution processes under crop canopies; however, these studies reveal inconsistent results with respect to canopy interception, with variations across the globe. Among crops, maize, which has a high yield and wide adaptability, is important in dryland systems. Maize can be grown under both irrigated and arid conditions from the tropics to temperate regions (Liu et al., 2015; Nazari et al., 2019). In the last 30 years, for example, the growing area of maize croplands has increased from 78.6 to 2323.5 km^2 in Iran (Nazari et al., 2019). The area of winter wheat croplands has decreased by 5730.7 km^2 over the last 20 years in Shaanxi Province, China, while that of spring maize croplands, one of the other main crops, has increased slightly. Zheng et al. (2018a) found that canopy interception accounted for 12.5% of cumulative gross precipitation during the whole growing season of maize in northwestern China. Nazari et al. (2019) reported that interception by the maize canopy can significantly reduce total water input to the surface in Tehran, Iran (19.9% of natural precipitation). Maximizing utilization of limited rainwater resources in rainfed agricultural areas is critical to increasing agricultural productivity (Zheng et al., 2018b). Maize canopies have an impact on the regional water cycle by modifying the distribution of water applied during precipitation (Nazari et al., 2019). As a result, the canopy interception of maize should be given more consideration, particularly in rainfed agricultural areas.

We searched the *Web of Science* (www.webofscience.com) for peer-reviewed articles published in English from 1995 to 2022 using the phrases "maize interception" and "corn interception" (Appendix B). For inclusion in our study, primary studies had to meet the following criteria: (1) data were obtained from maize at the individual or ecosystem level; (2) for studies only reporting throughfall and stemflow, interception was calculated as the difference between the total amount of precipitation and the sum of throughfall and stemflow. A dataset of 27 articles was compiled from the 1486 bibliographic references based on these criteria. The systematic literature search revealed that there is a gap in the field in relation to quantifying the relative importance of factors affecting maize canopy interception, so maize canopy interception requires further study. To improve our current understanding of the consequences of the interaction between precipitation and maize canopies and inspired by the newly reported ability to estimate the individual predictors across all response variables (Lai et al., 2022), we aimed to: (1) determine canopy interception and the ratio of interception to precipitation in maize cropland from a series of 80 precipitation events in a rainfed agricultural area; (2) quantify the individual contributions of different groups of factors and individual variables including meteorological factors and plant traits on canopy interception in maize cropland.

2. Materials and methods

2.1. Site description

To better understand the canopy interception process, detailed measurements were undertaken in the Wangdonggou watershed, Changwu tableland on the southern Loess Plateau in northwestern China (35°12′ N, 107°40′ E, 1219.0 m a.s.l) (Fig. 1). The watershed is flat, with an unsaturated soil depth of more than 50 m on average. The climate is temperate continental with rainy summers and dry winters, and droughts occur frequently. The mean annual precipitation is 519.6 mm (period 2000–2018). The precipitation from June to September accounts for about 55–78% of the annual total. There is no irrigation water in this region, so precipitation is the only water resource for vegetation growth. The mean annual temperature is 9.1 °C, the mean annual hours of sunshine over 2230 h and the frost-free period approximately 171 days. The maize was planted at an intermediate density of 66,660 plants/ha, with a row spacing of 50 cm and plant spacing of 30 cm. The field management schedule (i.e., application of fertilizer and weed control) was based on the local standard management.

2.2. Meteorological variables

Meteorological variables were measured from 2017 to 2020. Each precipitation event was measured continuously by an automatic meteorological station with 0.1 mm resolution, located approximately 300.0 m away from the experimental plots. In the present study, an individual precipitation event is considered to be one separated by at least 4.0 h from the next. The air temperature (AT, °C), relative humidity (RH, %) at a height of 2 m and wind speed (Ws, m/s,) at a height of 10 m were also monitored by the meteorological station (M520, Vaisala Company, Finland). To understand the synergistic effect of AT and RH, the vapor pressure deficit (VPD, kPa) was calculated (Campbell and Norman, 1979). The evaporation coefficient (E, unitless) was calculated to present the evaporation intensity based on the aerodynamics approaches (Carlyle-Moses and Schooling, 2015; Yuan et al., 2019).

$$es = 0.611 \times \exp((17.502 \times AT)/(AT + 240.97))$$

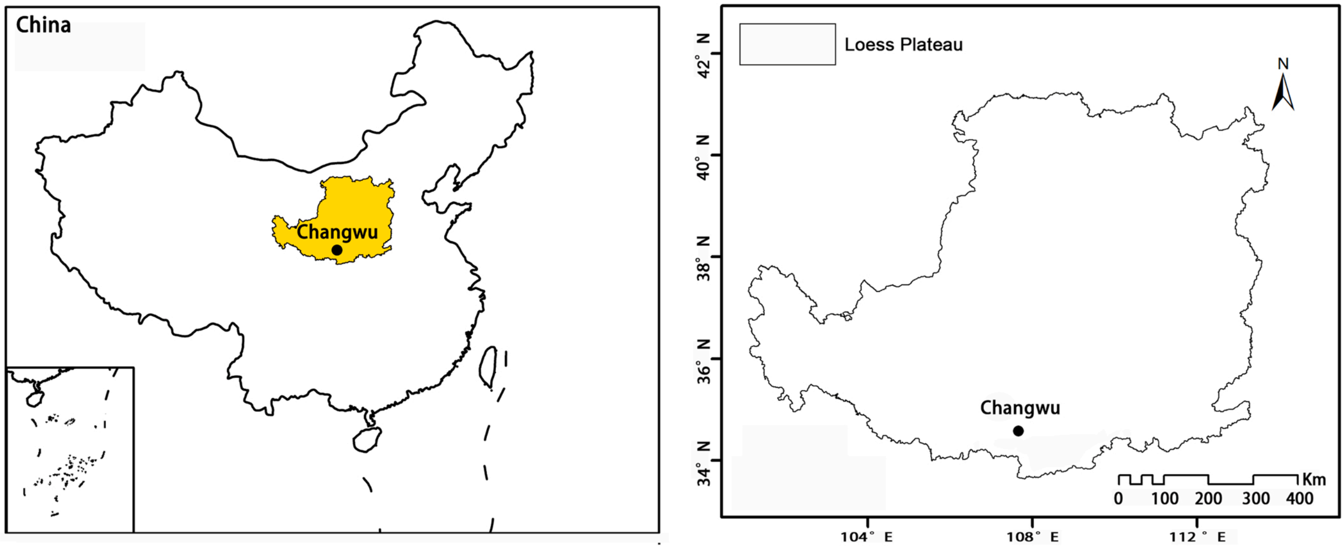

Fig. 1. Location of the study area and sampling sites on the Loess Plateau.

$$VPD = es - ((es \times RH)/100)$$

$$E = Ws \times VPD$$

Where *es* is the saturation vapor pressure (kPa).

By assuming the raindrop to be a perfect sphere (Uijlenhoet and Torres, 2006), raindrop diameter (D_{50}, mm) (Laws and Parsons, 1943), terminal raindrop velocity (U_V, m/s) (Gunn and Kiner, 1949) and average downward force (F_0, mg m/s) (Brandt, 1990) was calculated.

$$I = P/Dur$$

$$D_{50} = 2.23 \times (0.03937 \times I)^{0.102}$$

$$U_v = (3.378 \times \ln(D_{50})) + 4.213$$

$$F_0 = (1/6 \times \rho\pi D_{50}{}^3) \times U_v$$

Where I is the precipitation intensity (mm/h), P is the precipitation amount (mm), *Dur* is the precipitation duration (h) and ρ is the density of water.

Meteorological factors were divided into two categories: non-precipitation-related meteorological factors (NPMFs) and precipitation-related meteorological factors (PMFs). The specific factors included in each category were shown in Table 1.

Effective precipitation (P_{eff}) is the fraction of the total precipitation that is available to meet crop water needs, with deep percolation, surface runoff and interception loss excluded. The soil is deep (more than 50 m) and flat. The soils have a high infiltration capacity, with a steady infiltration rate of 1.35 mm/min. Therefore, the effects of surface runoff, subsurface runoff and deep seepage can be ignored. The simplified equation for P_{eff} estimation was:

$$P_{eff} = P - I_c$$

Measurement of I_c (canopy interception) will be described later.

Table 1
The specific factors included in each category.

Non-precipitation-related meteorological factors (NPMFs)	Precipitation-related meteorological factors (PMFs)
Atmospheric temperature (*AT*)	Precipitation amount (*P*)
Relative humidity (*RH*)	Precipitation duration (*Dur*)
Wind speed (*Ws*)	Precipitation intensity (*I*)
Vapor pressure deficit (*VPD*)	Raindrop diameter (D_{50})
Evaporation coefficient (*E*)	Terminal raindrop velocity (U_V)
	Average downward force (F_0)

2.3. Plant traits

The mean growth period of maize is about 150 days from mid-April to mid-September in this study. The sowing dates were 16 April, 20 April, 16 April and 19 April in 2017, 2018, 2019 and 2020, respectively. Maize has an upright stalk and is usually unbranched. The leaf blades are flat and broad, with a linear-lanceolate shape. The leaves are covered with pubescent hairs, the midribs are thick, and the leaf edges are slightly rough. The specific characteristics of normally growing maize are presented in Table 2.

Both the leaf area index (LAI) and the mean leaf inclination angle (MTA) were obtained by photographing the canopy with an optical fisheye digital camera (Nikon D7200 + Nikon AF DX 10.5 mm f/2.8 G ED) each week. To avoid the influence of rapid changes in the light environment and low color contrast between the blue sky and green plants on measurement results, canopy photographs were taken on cloudy and sunny days before sunrise or after sunset. The sampling was randomly repeated three times in each plot located at the center or 1/4 of the way along the diagonal of the plot. The camera was kept horizontally on a tripod when shooting and the shooting direction was determined by the height of the maize. The lens field of view should not cover the parts outside the sample site, and the operator's body parts should not be included in the photograph. LAI and MTA data were

Table 2
The morphological traits of sample maize at the end of vegetative growth.

Average height (cm)	Average basal diameter (cm)	Average widest part of leaf (cm)	Average length of leaf (cm)
310.2	4.9	10.4	68.2
319.6	5.3		
321.1	5.3		
309.2	4.5		
314.8	4.8		
316.9	5.1		
308.4	4.5		
311.0	4.5		
315.4	4.7		
309.8	4.6		
316.0	5.0		
317.1	5.1		

processed and the values calculated by CAN_EYE software v6.47. Eight clear photographs were selected for processing. The illumination effect could be ignored because the photographs were taken in conditions of uniform light and no direct light. Latitude, longitude, slope, and terrain are all entered based on the actual situation at the measuring point. Calibration experiments for the optical center and projection function were required for a given camera+fish-eye system, according to the user manual (https://www6.paca.inrae.fr/can-eye).

2.4. Canopy interception measurement

The amount of canopy interception (I_c) was obtained indirectly by measuring the amount of throughfall and stemflow. All of I_c was assumed to be lost to evaporation in the study. The periods during which maize canopy interception was measured were from 5 July to 11 September 2017, 9 July to 5 September 2018, 28 June to 17 September 2019 and 27 June to 10 September 2020. The maize cropland is 49.5 m long and 20.0 m wide, with a total area of 990 m^2. Each experimental maize plot was 16.5 m long and 10.0 m wide, with six plot replicates. Throughfall was measured at one point in each plot using horizontal iron troughs, 90.0 cm long and 50.0 cm wide. The iron trough was positioned between rows at the center of each plot. Two maize plants in the center of each plot were used to obtain the stemflow. Stemflow was collected using a breathable but dense sponge funnel affixed to the stem of each sample maize plant at a height of 30 cm to ensure the normal growth of maize and the funnel was sealed by neutral silicone caulking. The funnel was tightly connected to the stalk and sealed with neutral silicone. The simulated water flow was used to determine if there was any leakage after the silicone solidified. The diameter of funnel was controlled to the minimum to avoid overestimating stemflow by collecting throughfall. A pipe with a diameter of 1.2 cm was used to connect the collection device and the storage container and channeled stemflow from the funnel to container with minimum travel time. The amounts of throughfall stored in the iron troughs and stemflow in the containers were manually weighed. If the precipitation events ended during the daytime, the collection of throughfall and stemflow was usually completed within two hours after the end of events. To minimize evaporation, if the precipitation events ended at night, the collection of throughfall and stemflow was completed as soon as possible in the next morning. These apparatuses were periodically checked against leakages or blockages caused by insects and fallen leaves. Throughfall and stemflow volumes were converted to equivalent water depth using the iron trough bottom area and maize canopy area, respectively.

Therefore, the canopy interception (I_c) was obtained and calculated as follows:

$$I_c = P - TF - SF$$

where P is the precipitation (mm), TF is the throughfall (mm), and SF is the stemflow (mm).

2.5. Statistical analyses

To determine the relative importance of each group (PMFs, NPMFs and plant traits) independently or in combination, variation partitioning and hierarchical partitioning based on canopy interception were used (Yang et al., 2019; Lai et al., 2022). Canopy interception as the response variable was applied to partitioning of variation, and the separate contributions obtained were: variation explained by PMFs independent of NPMFs and plant traits; variation explained by NPMFs independent of PMFs and plant traits; variation explained by plant traits (LAI, MTA) independent of PMFs and NPMFs. The PMFs were then subdivided into two groups in order to explore the effect of precipitation characteristics and raindrop characteristics on I_c: (1) precipitation event factors: factors related to precipitation event, i.e. precipitation amount, duration and intensity; (2) raindrop factors: factors related to raindrops i.e. D_{50}, U_V, and F_0. These analyses were carried out in R software using the "rdacca.hp" library (Lai et al., 2022). SPSS 24.0 statistical software was used for the statistical analyses (SPSS Inc., Chicago, USA). Origin 2018 (OriginLab Corporation, USA) for Windows and R software were used to create all of the figures.

3. Results

3.1. Characteristics of the precipitation and non-precipitation-related meteorological factors

The probability density and cumulative distribution of PMFs and NPMFs are presented in Fig. 2. The precipitation amount ranged from 0.1 to 67.7 mm for the 80 events, with a total of 1055.5 mm and an average of 13.2 mm. The most likely precipitation event had 2.8 mm of precipitation. The duration varied from 1.0 to 84.0 h. The most likely precipitation event duration was 3 h. There were 50 events with light precipitation (0.5–2.5 mm/h) over the whole experimental period. The most likely precipitation event had an intensity of 0.4 mm/h. The D_{50} ranged from 1.3 to 1.9 mm, with a mean of 1.5 mm. The U_V ranged from 4.6 to 5.1 mm/s. The most likely precipitation event had a velocity of 4.9 mm/s. The mean F_0 was 10.1 mg m/s. The mean E was 0.3. The mean AT was 20.0 °C, with the highest probability density approximately 18.7 °C. The mean RH was 88.2% over the experimental period. The Ws ranged from 0.1 to 2.2 m/s, with an average of 1.2 m/s and the highest probability density approximately 0.9 m/s. The VPD was 0.3 kPa on average.

3.2. Characteristics of the plant traits

Fig. 3 shows the LAI and MTA dynamics of maize cropland over the whole experimental period. Leaf area index represents the density of leaves in the canopy. LAI exhibited an increasing trend to a maximum value, which then gradually decreased. The mean LAI was 3.3 during the observation period. The MTA is the angle formed by the intersection of the surfaces of leaves and flat ground. The MTA ranged from 21.3° to 66.0°, with a mean of 51.1°.

3.3. Canopy interception characteristics

Over the measurement period, a total of 80 precipitation events were recorded and measured for I_c analysis (Fig. 4). The I_c of the precipitation events ranged from 0.1 mm to 29.1 mm, with an average of 4.9 mm. The cumulative I_c of the 80 events was 395.9 mm, accounting for 39.7% of the cumulative precipitation amount (996.3 mm). There were 23 events where the precipitation was completely intercepted, accounting for 1.5% of the total precipitation amount. On average, I_c accounted for 57.6% of precipitation during the events; after excluding the precipitation events less than 5 mm, I_c accounted for 37.3% of precipitation during the events. The I_c percentage was highest in the light precipitation events (0–5 mm), and then decreased. When the precipitation was less than 2.0 mm, the I_c percentage was at its maximum (85.6%), while when it was greater than 15.0 mm, the I_c percentage was at its minimum (36.8%). The frequency distributions of interception amount show that light and heavy precipitation events ($\leq$ 2.0 mm and > 15 mm) were far more common than moderate events. The relationship between calculated effective precipitation and precipitation for the maize cropland for all 80 precipitation events is shown in Fig. 5. Significant linear relationships were found between effective precipitation amount and precipitation amount.

3.4. Correlations between canopy interception and the measured variables

The I_c showed significant positive correlations with all PMFs, while I_c percentage showed significant negative correlations with all these factors according to Pearson correlations analysis ($p < 0.01$) (Fig. 6). The I_c

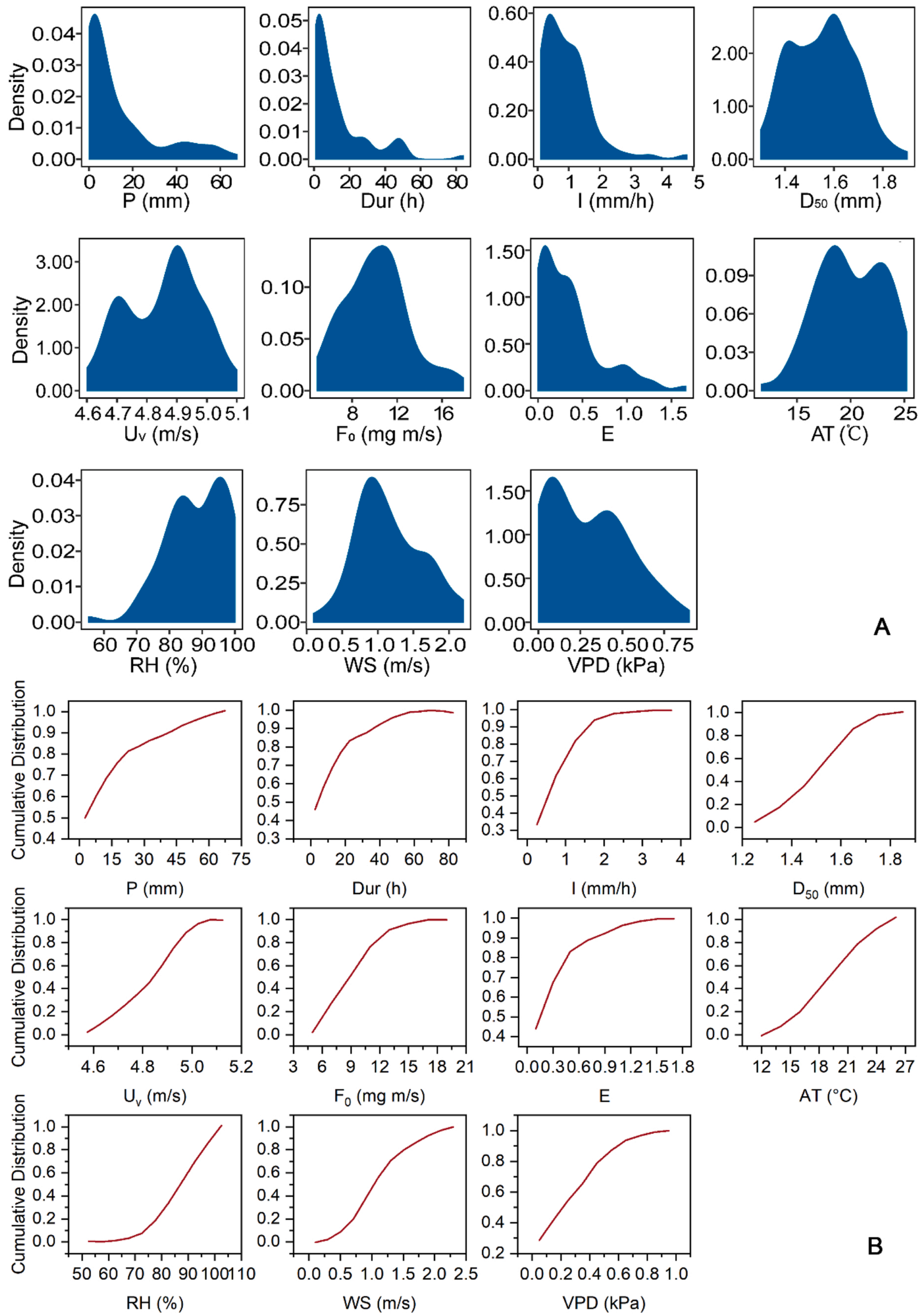

Fig. 2. Probability density (A) and cumulative distribution (B) of precipitation-related and non-precipitation-related meteorological factors. *P*: precipitation amount, *Dur*: precipitation duration, *I*: precipitation intensity, D_{50}: average raindrop diameter, U_v: terminal raindrop velocity, F_0: average downward force, *E*: evaporation coefficient, *AT*: atmospheric temperature; *RH*: relative humidity; *WS*: wind speed; *VPD*: vapor pressure deficit.

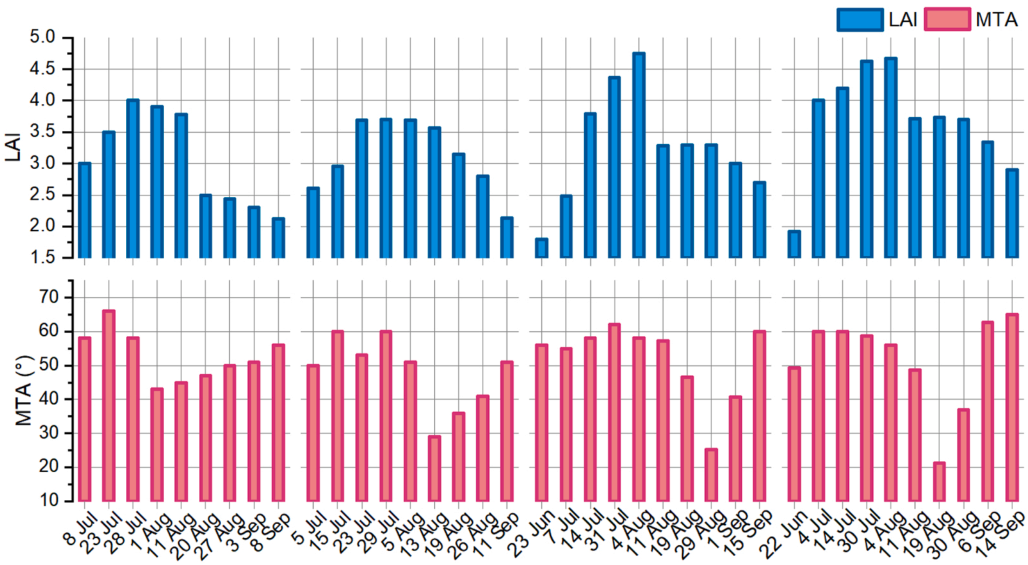

Fig. 3. Distribution of leaf area index (LAI) and mean leaf inclination angle (MTA).

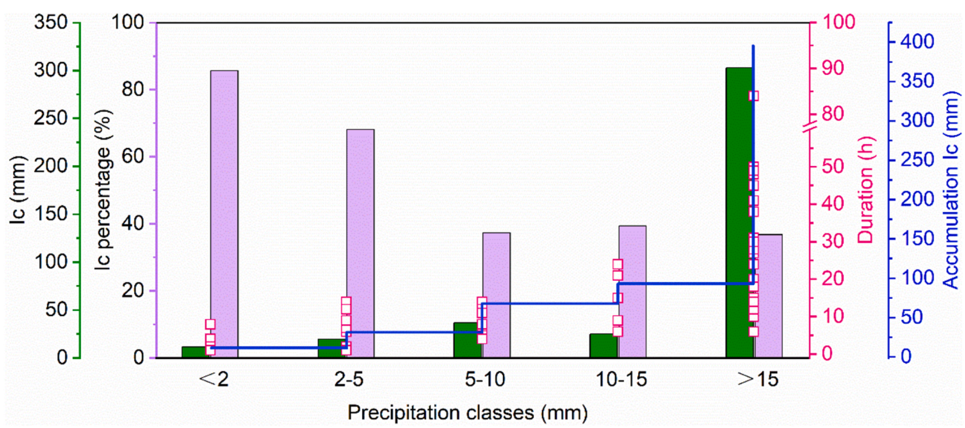

Fig. 4. The canopy interception (I_c) and the proportion of canopy interception of precipitation (I_c percentage) under each precipitation class.

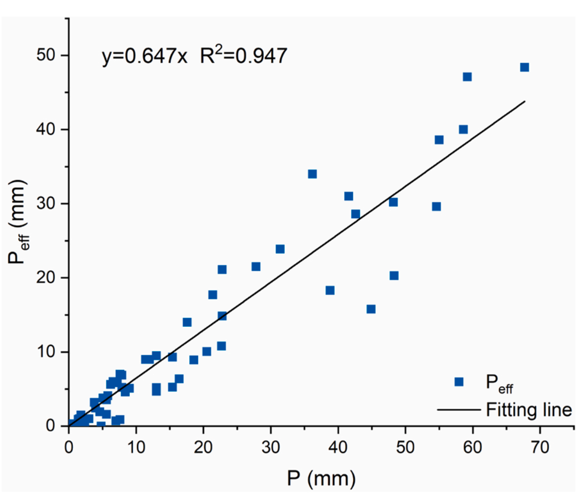

Fig. 5. Relationship between precipitation amount (*P*) and effective precipitation amount (P_{eff}) for all eighty precipitation events.

and I_c percentage showed significant correlations with *RH* and *VPD* from the NPMFs factors at a significance of 0.01. Furthermore, I_c was significantly negatively correlated with *AT* ($p < 0.05$) and *E* ($p < 0.01$). Other factors, besides precipitation amount, were found to have no significant partial correlation with I_c. There was no partial correlation between I_c percentage and any of the factors studied. There was no significant correlation between I_c or I_c percentage and LAI or MTA, whether using Pearson correlation analysis or partial correlation analysis.

3.5. Influence of grouping characteristics on interception

The variables were divided into three groups: PMFs, NPMFs and plant traits. When NPMFs and plant traits were excluded, the results of variation partitioning showed that the unique effect of PMFs on I_c and I_c percentage was 47.3% and 35.9%, respectively (Fig. 7A, C). The unique effect of NPMFs or plant traits on I_c and I_c percentage was small. The common effects of PMFs and NPMFs accounted for 30.1% of variation in I_c and 8.6% in I_c percentage. The common effects of PMFs and plant traits or NPMFs and plant traits was less than 1.0% both for I_c and I_c percentage. The common effect of the three groups on I_c percentage (2.9%) was greater than on I_c. PMFs had the greatest individual importance on I_c and I_c percentage, respectively ($p < 0.01$) (Table 3). However, the individual importance percentage of PMFs on I_c percentage was greater than on I_c. The individual importance of plant traits was

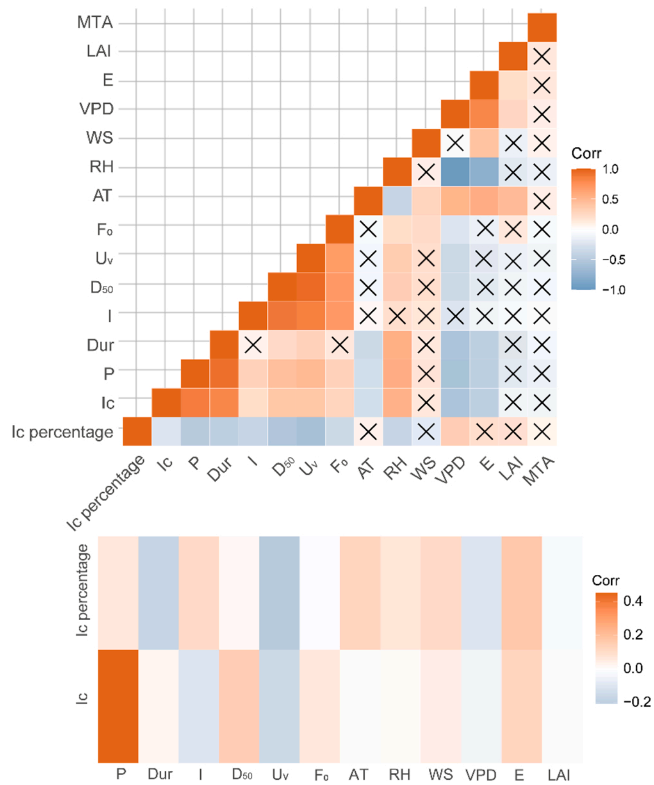

Fig. 6. Pearson and partial correlation matrixes between the amount and percentage of interception and different variables. A: The Pearson correlation matrix, B: The partial correlation matrix, I_c: the amount of canopy interception, I_c percentage: the proportion of the precipitation during each event that is intercepted, *P*: precipitation amount, *Dur*: precipitation duration, *I*: precipitation intensity, D_{50}: average raindrop diameter, U_v: terminal raindrop velocity, F_0: average downward force, *AT*: atmospheric temperature; *RH*: relative humidity; *WS*: wind speed; *VPD*: vapor pressure deficit, *E*: evaporation coefficient, LAI: leaf area index. MTA: mean leaf inclination angle. Number of events: 80.

less than 0.3% both on I_c and I_c percentage. The residual portion of the three groups on I_c was 24.9%, whereas the common effects of the three groups was only 43.0% on I_c percentage.

When the variables were divided into four groups: precipitation event factors, raindrop factors, NPMFs and plant traits, precipitation event factors had the highest unique effect (42.3%) and the highest average shared importance (14.1%) on I_c, while raindrop factors had the second highest unique effect (1.0%) on I_c (Fig. 7B). Raindrop factors had the highest unique effect (18.9%) and the second highest average shared importance (9.3%) on I_c percentage (Fig. 7D). The highest common effect of two groups was precipitation event factors and NPMFs, for which the effect was 15.0% on I_c; however, the highest common effect of two groups for I_c percentage was precipitation event factors and raindrop factors (14.6%). The common effect of precipitation event factors and raindrop factors on I_c was 4.0% and the other common effects of any two groups were all less than 1.0% for I_c or I_c percentage. Precipitation event factors had the highest individual importance (56.4%, $p < 0.001$) on I_c, followed by NPMFs (Table 3). Raindrop factors had the highest individual importance (28.3%, $p < 0.001$) on I_c percentage, followed by precipitation event factors.

The 38 precipitation events close to the date when the LAI and MTA were measured were chosen to examine variation partitioning and hierarchical partitioning to further confirm the effect of plant traits on I_c (Fig. 8). When the results for all 80 precipitation events were compared, the unique effect of plant traits on I_c and I_c percentage increased for these 38 events, with an increase of more than 5.0% and 19.0%, respectively. PMFs, however, still had the greater unique effect and individual importance compared to NPMFs and plant traits (Fig. 8, Table 3). The residual portion was 27.8% and 51.6% for I_c and I_c percentage, respectively.

3.6. Influence of variables on interception

The adjusted R^2 of variation partitioning with all 14 factors was 0.751 on I_c (Table 4). Although the total variation was relatively high (75.1% adjusted), most of this variation was shared among predictors (0.692 or 69.2%) and the unique contributions of factors were generally small. The total was 75.1% (i.e. 69.2% + 5.9% = 75.1%). The adjusted R^2 of variation partitioning with all 14 predictors was 0.433 on I_c percentage. The total contribution was 43.3% (i.e. 44.7% + (−1.4%) = 43.3%). In this study, precipitation amount had the highest individual importance on I_c (30.2%, or 40.3% of the total R^2, $p < 0.01$). This is the result of precipitation amount having the highest unique effect (5.4%) and the highest average shared importance (24.8%). Duration had the second highest individual importance (22.9%, $p < 0.001$) and average shared importance (23.2%), but its unique contribution was quite low. The unique and individual contributions of LAI and MTA were both negative. On I_c percentage, D_{50} had the highest individual importance (9.5%, $p < 0.05$), followed by U_V (9.4%, $p < 0.001$), and F_0 (8.4%, $p < 0.001$). This is the result of D_{50}, U_V and F_0 having a high average shared importance (9.8%, 9.5%, 9.1%). The individual importance of these factors was primarily from average shared importance, and varied slightly. As we determined that the amount and duration of precipitation contributed greatly to I_c, and LAI was enhanced in its contribution to canopy interception when only the 38 precipitation events near the measurement date of LAI were used, we obtained an equation for predicting I_c by multiple linear regression as follows:

$$I_c = -0.0675 \times Dur + 0.1271 \mathrm{LAI} \times P$$

The equation can predict interception amount from precipitation amount (*P*), duration (*Dur*) and LAI, where $R^2 = 0.779$ and $p < 0.001$ (Fig. 9).

4. Discussion

4.1. Interception in relation to correlation variables

Some significant changes in recorded precipitation in this region have occurred as a result of climate change (Zhang et al., 2021a). The amount and intensity of precipitation ranged from 0.1 to 67.7 mm and 0.1–4.8 mm/h, respectively, indicating high temporal variability of precipitation events. Precipitation events that occurred in this region were characterized by being of relatively short duration (mean 3 h). In this study, most of the raindrops had a diameter ranging from 1.6 mm and 1.7 mm and were classified as moderate-sized (1–3 mm) (Liu et al., 2018). Raindrop characteristics tended to be related to intensity, with higher intensity associated with increased D_{50} and U_V. F_0 was not only related to D_{50}, but also to U_V when raindrops reached the canopy (Li et al., 2019). These precipitation event properties meant that rainwater was more likely to be lost while wetting the canopy surface and less likely to pass through the maize crown. These findings reflect the uncertainty of the hydrological regime that is common in water limited regions, as verified by Andrade et al. (2016).

In this study, the mean I_c and I_c percentage per event were 4.9 mm and 57.6% for maize cropland, respectively. These results were within the range of 1.7–63.4% for maize, reported by Frasson and Krajewski (2013) and Nazari et al. (2019). The values were, however, slightly higher than the results obtained by Zheng et al. (2018a) and Wang et al. (2016). Rainfall intensity in our study (mean 1.0 mm/h) was generally lower than in the above studies, meaning that a large amount of precipitation was intercepted and evaporated during (Yan et al., 2019). These results also indicated that a greater variation in I_c occurs between different precipitation events, therefore, analyzing I_c on an event basis is

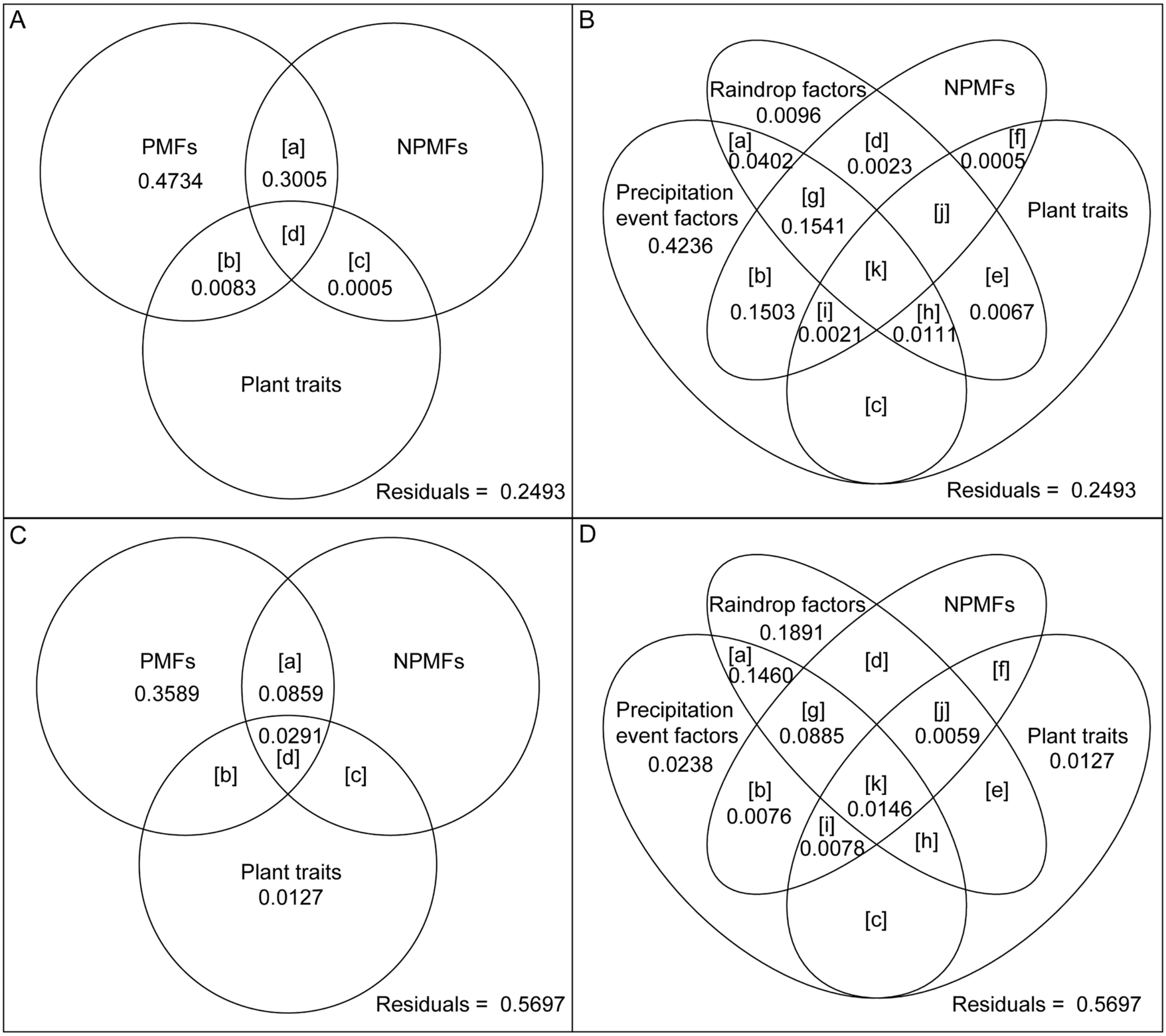

Fig. 7. Variation partitioning and hierarchical partitioning results for variable groups in relation to canopy interception amount (A, B) and percentage (C, D). A, C: [a]–[d] indicate the common explanations of the variables. B, D: [a]–[k] indicate the common explanations of the variables. The unique effects and combined effects for which no values are given were negative. PMFs: Precipitation-related meteorological factors, NPMFs: Non-precipitation-related meteorological factors.

preferable to analyzing I_c over a growing season or whole year. Indeed, Brasil et al. (2018) demonstrated that the I_c percentage was the same in different years, but the amount varied greatly. Ignoring the canopy intercepted loss by maize or lumping it with evapotranspiration, may have a noticeable effect on the results of water balance estimates. In addition, the I_c for maize cropland differs from figures reported in studies of shrubs and forests conducted in similar climatic regions. For example, Zhang et al. (2017) found that the I_c of a *Hippophae rhamnoides* stand ranged from 0.40 to 4.39 mm per event, with an upper limit of about 21% of the total precipitation on the Loess Plateau. Wang et al. (2005) found that the average interception of a shrub community during the growing season was 6.9% for *Artemisia ordosica* Krasch. and 11.7% for *Caragana korshinskii* Kom. According to Wang et al., (2018), the total I_c of an apple orchard was 26.8–39.9 mm from May to September. Measurements of interception performed in California with pear and cork oak trees revealed that these species intercepted 15% and 27% of precipitation, respectively (Xiao et al., 2000). The difference in interception loss between maize and shrubs or forests highlights species-specific differences.

The amount and proportions of I_c for maize were statistically significantly correlated with PMFs in general, including amount, duration, intensity and raindrop factors; these results are consistent with those of Zhang et al. (2016) and Zheng et al. (2018a). A negative correlation between percentage interception and amount of precipitation demonstrated that the vegetation becomes saturated as precipitation persists, as reported by Brasil et al. (2018). Rainfall intensity determined the amount of interception per unit time, which also reflects the dynamic energy on the leaf surface (Zheng et al., 2018a). Higher intensity rainfall increased the possibility of a raindrop falling from leaves and passing through canopy gaps, resulting in a decrease in I_c percentage. Our results showed that there were correlations between *RH*, *VPD* and I_c, which is consistent with Zheng et al. (2018a), Zhang et al. (2015) and Grunicke et al. (2020). Staelens et al. (2008) found that *Ws* increased intercepted precipitation. Zabret and Sraj (2019) reported that the different response of I_c to *Ws* could be attributed to the different vegetation characteristics of the observed trees as well as their location.

Table 3
Hierarchical partitioning results for the influence group of canopy interception.

	Group	Canopy interception (mm)			Canopy interception percentage (%)		
		Individual importance	I.perc (%)[a]	p-value[b]	Individual importance	I.perc (%)[a]	p-value[b]
Three groups[c]	PMFs	0.622	82.93	0.01 * *	0.399	92.57	0.01 * *
	NPMFs	0.135	18.00	0.05 *	0.029	6.73	0.21
	Plant traits	-0.007	-0.93	0.49	0.003	0.70	0.33
Four groups[d]	Precipitation event factors	0.564	75.20	0.01 * *	0.133	30.86	0.01 * *
	Raindrop factors	0.082	10.93	0.05 *	0.283	65.66	0.01 * *
	NPMFs	0.112	14.93	0.05 *	0.013	3.02	0.33
	Plant traits	-0.008	-1.06	0.46	0.002	0.46	0.35
Selected events[e]	PMFs	0.598	82.94	0.01 * *	0.298	61.57	0.01 * *
	NPMFs	0.107	14.84	0.15	0.052	10.74	0.27
	Plant traits	0.016	2.22	0.27	0.134	27.69	0.05 *

*, **significance at $p < 0.05$, < 0.01, respectively.
[a] Individual effect divided by total adjusted R^2 value in column "Individual importance";
[b] p-values according to permutation test based on 299 randomizations. The values can vary from one run to another;
[c] Note: The variables were divided into three groups to determine the individual importance;
[d] The variables were divided into four groups to determine the individual importance;
[e] The precipitation events close to the measurement date of LAI and MTA;

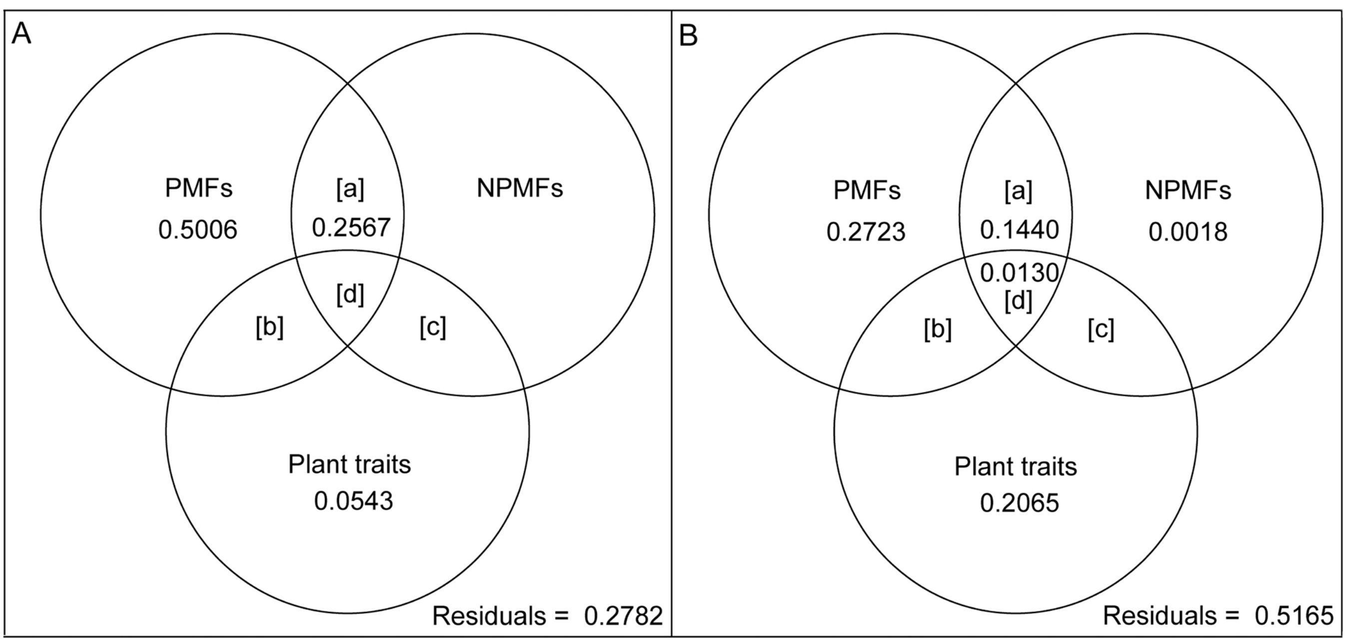

Fig. 8. Variation partitioning and hierarchical partitioning results for variable groups in relation to canopy interception amount (A) and percentage (B) among leaf area index-related precipitation events. [a]–[d] indicate the common explanations of the variables. The unique effects and combined effects for which no values are given were negative. PMFs: Precipitation-related meteorological factors, NPMFs: Non-precipitation-related meteorological factors.

Because the *Ws* in our study area was generally around 1.0 m/s, the effect on I_c was minimal.

Some studies of trees and shrubs have found positive correlations between I_c and LAI (Liu et al., 2018; Brasil et al., 2018; Yan et al., 2021), which is slightly different from our results. This could be a species-related difference. There was no significant relationship between MTA and I_c or I_c percentage, because the maximum change in MTA, after raindrop impact, is a function of species and D_{50} (Yan et al., 2020; Ginebra et al., 2020). The leaf hairs of maize may enhance the stability of MTA against raindrop impact, i.e. the leaf biomechanical properties have an effect (Holder et al., 2020). Holder et al. (2020) indicated that increasing D_{50} from 2.7 mm to 3.9 mm resulted in an increased maximum change in MTA. The leaf inclination angle for *Quercus gambelii* Nutt. barely changed after each 2.7 mm raindrop drop impact. In our study, D_{50} was generally less than 2.0 mm. However, the variation in MTA changes upon raindrop impact between species should be considered, and this may be helpful in understanding the dynamic precipitation interception process.

4.2. Selection of groups and indicators for the interception process

There is still no consensus about the relative importance of precipitation event factors, raindrop factors, NPMFs and plant traits in studies quantifying plant interception. Using variation partitioning and hierarchical partitioning analysis, precipitation properties were found that have more unique effects and individual contributions than NPMFs and plant traits on maize I_c, which agrees with previous findings (Staelens, et al., 2008; Zhang et al., 2016; Grunicke et al., 2020). We separated out the raindrop factors within the PMFs, and found that the individual contribution of the raindrop factors only explained 8.2% of the I_c. The results convinced us that precipitation event factors had a greater impact on I_c than raindrop factors.

The effects of different groupings differed between I_c and I_c percentage. For example, when the factors were divided into three groups,

Table 4
Variation partitioning and hierarchical partitioning results for the influence variables of canopy interception.

Variables	Canopy interception (mm)					Canopy interception percentage (%)				
	Unique	Average.shared[a]	Individual importance	I.perc (%)[b]	p-value[d]	Unique	Average.shared[a]	Individual importance	I.perc (%)[b]	p-value[d]
P	0.054	0.248	0.302	40.30	0.01 * *	-0.006	0.044	0.038	8.84	0.05 *
Dur	-0.004	0.232	0.229	30.44	0.01 * *	0.003	0.037	0.040	9.30	0.05 *
I	-0.004	0.013	0.010	1.28	0.20	0.010	0.043	0.054	12.44	0.04 *
D_{50}	0.013	0.017	0.030	4.00	0.08	-0.003	0.098	0.095	21.98	0.02 *
U_V	0.017	0.016	0.032	4.35	0.07	-0.000	0.095	0.094	21.86	0.01 * *
F_0	-0.002	0.023	0.022	2.90	0.14	-0.007	0.091	0.084	19.51	0.01 * *
AT	-0.003	0.009	0.007	0.92	0.24	-0.002	0.001	-0.001	-0.33	0.32
RH	-0.002	0.048	0.046	6.14	0.05 *	-0.006	0.022	0.015	3.44	0.17
WS	0.003	0.006	0.002	0.31	0.24	-0.003	0.000	-0.002	-0.56	0.33
VPD	-0.002	0.052	0.051	6.74	0.03 *	-0.008	0.018	0.010	2.26	0.19
E	-0.004	0.029	0.026	3.42	0.10	-0.008	0.006	-0.002	-0.35	0.35
LAI	-0.002	0.001	-0.001	-0.15	0.49	0.017	-0.004	0.013	2.91	0.17
MTA	-0.004	-0.002	-0.005	-0.65	0.47	-0.001	-0.004	-0.005	-1.23	0.49
Total	0.059	0.692	0.751	100		-0.014	0.447	0.433	100	

* , * *significance at $p < 0.05$, < 0.01, respectively
[c]p-values according to permutation test based on 299 randomizations. The values can vary from one run to another;
[a] Note: Total average shared effects with other factors.
[b] Individual effect divided by total adjusted R^2 value in column "Individual importance".

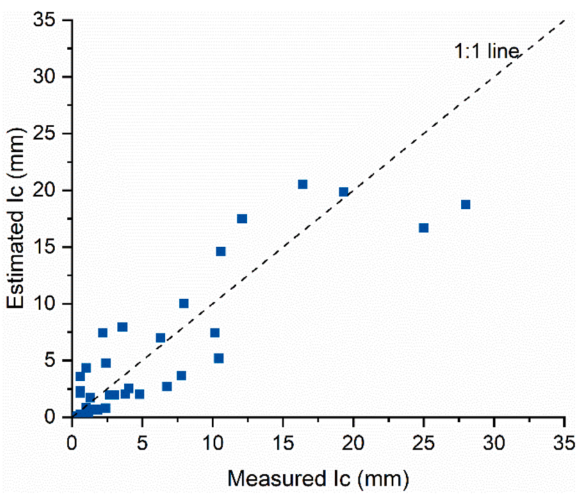

Fig. 9. Comparison between the predicted and measured values of canopy interception. I_c: canopy interception amount, number of events: 38.

the unique effects of plant traits on I_c percentage were greater than on I_c; the difference in I_c and I_c percentage could be explained by the fact that the plant canopy has an impact on precipitation redistribution (Zheng et al., 2018a). The individual importance percentage of PMFs on I_c percentage was greater than I_c, because the I_c percentage included I_c and precipitation, and the PMFs have more effect on precipitation. When the variables were divided into four groups, it was found that the relative importance of raindrop factors on the I_c percentage increase compared with that on I_c, regardless of unique contributions or individual importance. One explanation could be that the characteristics of raindrops, such as diameter and kinetic energy, played an important role in raindrops passing through the canopy (Zhang et al., 2016). When the results of different groups were compared, the highest contributions to explaining I_c and I_c percentage were precipitation event factors and raindrop factors, respectively.

Precipitation amount and duration, the two most important factors, worked against each other to drive precipitation partitioning into canopy interception; this result is consistent with previous studies (Brasil et al., 2018; Nazari et al., 2019). Earlier studies have found that factors such as *AT*, *RH*, and *Ws* have a significant impact on the canopy's water storage capacity. Zhang et al. (2015) concluded that NPMFs were not significantly correlated with precipitation partitioning in the 0–30 mm precipitation range. Moreover, only certain individual contributions of *RH* and *VPD* were found on I_c and there was no individual contribution of *RH* and *VPD* to the I_c percentage. The effects of NPMFs may be offset by the interaction of other significant factors, leading to a non-significant contribution to explaining I_c. Raindrop factors explained a total of about 28.3% of the individual contribution, which indicated the non-negligible role of raindrop factors in determining I_c percentage. The D_{50} effect was the result of the raindrops constantly hitting the leaf surfaces and the water droplets dispersing, which affected the ratio of I_c and effective precipitation in precipitation partitioning. The effect of U_v and F_0 on I_c percentage was similar to D_{50}, the reduction in canopy wetting with increased U_v and F_0 could be attributed to splashing caused by the greater kinetic energy of the larger drops (Yan et al., 2021). Therefore, the higher I_c percentage for rainfed maize cropland was mostly attributed to two causes, namely the frequency and duration of light precipitation events, as well as the relatively smaller raindrop diameter and downward force.

By examining the precipitation events close to the date when maize LAI was measured, we found that the contribution of plant traits to explaining I_c, particularly I_c percentage, was increased. The results highlight the importance of maize's large crown volume and water-absorbing leaves (i.e., leaves covered by dense hairs) in canopy interception, as well as the significant influence of plant traits on raindrop characteristics. In addition, because of the obvious changes in maize leaf growth, correlations between LAI and I_c must be based on measurements taken close together, rather than a single LAI collected once in relation to interception determined over weeks or a long stage. As a result, frequent measurement of LAI is critical for studying the effects of changes in plant traits on interception. In general, the I_c can be predicted with a relatively high accuracy using precipitation amount, duration and LAI data (R^2 =0.779).

4.3. Implications for agroecosystem environments

Understanding the influence of an actively growing crop on canopy interception per event is important for agroecosystem and water management on the Loess Plateau and other similar water limited regions. Our results confirmed that interception by the maize canopy accounts for an important portion of the total field water input, and should not be ignored when determining water demand or irrigation schedules. The equation developed for estimating I_c achieved high accuracy using three parameters (precipitation amount, intensity and LAI). Combined with the P_{eff} equation, the amount of water available for maize growth and the amount of water that needs to be supplemented can be determined.

Because the numerical values of influencing factors presented in this study are fully quantified and we were able to separate the effects of groups and individual variables on I_c, they are useful for the modular development of hydrological models.

5. Conclusions

The analysis of this study was based on data from 80 events collected over a four-year period (2017–2020). Measurements were taken in maize cropland located on the southern Loess Plateau. The cumulative I_c of the 80 events accounted for 39.7% of the total precipitation. Canopy interception accounted for 57.6% of precipitation per event on average. The I_c percentage was highest during the light precipitation events (0–5 mm). All precipitation factors were found to have significantly positive correlations with I_c, while I_c percentage showed significantly negative correlations with all precipitation factors ($p < 0.01$). By comparing the variation partitioning and hierarchical partitioning results of different groups of factors, we found that precipitation event factors (precipitation amount, duration, intensity), contribute most to explaining I_c, and raindrop factors (D_{50}, U_V, F_0) contribute most to explaining I_c percentage. The common effect of precipitation event factors and non-precipitation-related factors on I_c was highest. When we considered only precipitation events close to the date of LAI measurement, the contribution of plant traits to I_c percentage increased and was much greater than for I_c. It is essential that short-term assessments are used if considering LAI in relation to I_c, longer-term extrapolations will be inaccurate. As a result, frequent LAI measurement of maize is required. The amount of precipitation best explained I_c (30.2%) and the D_{50} best explained I_c percentage (9.5%), according to variation partitioning and hierarchical partitioning analysis in relation to meteorological variables and plant traits. Most of this variation was shared by factors and the unique contributions of factors were generally low. Our findings highlight the importance of I_c in water limited areas and demonstrate the individual contributions of groups of factors and individual factors to I_c and I_c percentage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

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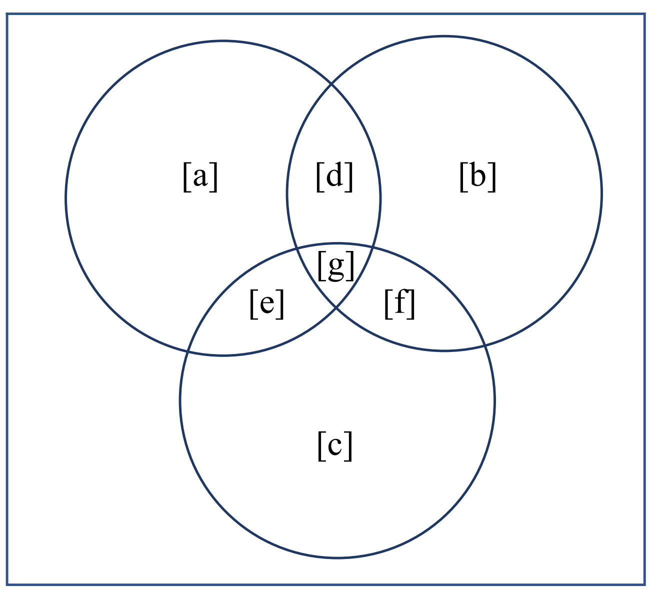
Appendix A



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Venn diagram representing the variation partitioning of a response matrix Y regressed against three correlated factors (or groups of predictors as in variation partitioning).

[a], [b] and [c] represent the unique effect on Y. [d], [e] and [f] represent the common effects of [a][b], [a][c], [b][c] on Y. The average shared effects of [a], [b] and [c] are half of all common effects involving [a], [b] and [c], respectively. The individual importance of [a], [b] and [c] are all of the effects involving [a], [b] and [c], respectively. [g] represents the common effects of [a], [b] and [c] on Y.

Appendix B

A dataset of 27 articles was compiled from the 1486 bibliographic references based on these criteria.

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